High precision locations of long-period events at La Fossa Crater (Vulcano Island, Italy)

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Abstract
Since the last eruption in 1888-90, the volcanic activity on Vulcano Island (Aeolian Archipelago, Italy) has been limited to fumarolic degassing. Fumaroles are mainly concentred at the active cone of La Fossa in the northern sector of the island and are periodically characterized by increases in temperature as well as in the amount of both CO_2 and He. Seismic background activity at Vulcano is dominated by micro-seismicity originating at shallow depth (<1-1.5 km) under La Fossa cone. This seismicity is related to geothermal system processes and comprises long period (LP) events. LPs are generally considered as the resonance of a fluid-filled volume in response to a trigger. We analyzed LP events recorded during an anomalous degassing period (August-October 2006) applying a high precision technique to define the shape of the trigger source. Absolute and high precision locations suggest that LP events recorded at Vulcano during 2006 were produced by a shallow focal zone ca. 200 m long, 40 m wide and N30-40E oriented. Their occurrence is linked to magmatic fluid inputs that by modifying the hydrothermal system cause excitation of a fluid-filled cavity.

Key words *LP – Seismology waveform correlation – source geometry – Volcano Sismology – Volcano Monitoring*

1. Introduction

The island of Vulcano (500 m a.s.l.) is a composite volcanic edifice located in the south-central sector of the Aeolian Archipelago (Tyrrhenian Sea, Italy). The island, together with Lipari and Salina Islands (fig. 1), represents the emerged part of the Tindari-Letojanni system (TL), a NW-SE elongated volcanic ridge affected by a right-lateral strike slip, moving in response to a N100E regional extension field (Mazzuoli *et al.*, 1995).

If the overall complex is mainly controlled by the TL system, the northern sector of Vulcano island is characterized by NE-SW and N-S trending normal structures which accommodate the horizontal movements of the main system (fig. 1) (Mazzuoli *et al.*, 1995). Along these two oblique trends are aligned the primary (dikes, vents and eruptive fissures) volcanic structures (Mazzuoli *et al.*, 1995; Ventura *et al.*, 1999).

Recent eruptions on the island have taken place at Vulcanello (1550) and La Fossa crater (1888-1890), with volcanic products consisting mainly of pyroclastic material with lesser volumes of lava flows. La Fossa is a 391 m high cone with a base diameter of 1 km whose historic activity has been characterized by frequent transitions from phreatomagmatic to minor magmatic activity.

After the last eruptive episode (1888-1890), volcanic activity has been restricted to fumarolic

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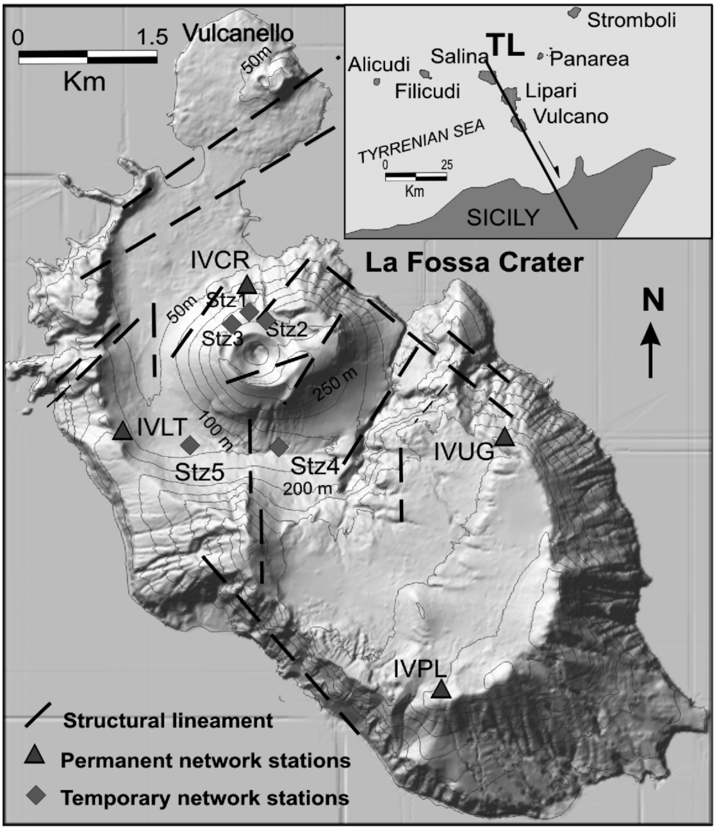

Fig. 1. Map of the Vulcano permanent and temporary seismic network. Structural lineaments from Mazzuoli *et al.*, (1995).

degassing, mainly at La Fossa with mean temperatures ranging between 200° and 300° C.

The origin of the geothermal system at Vulcano has been discussed by several authors using different approaches and chemical tracers (*e.g.* Chiodini *et al.,* 1995; Todesco, 1997; Capasso *et al.*, 1999; Paonita *et al.*, 2002 Gambino and Guglielmino, 2008); there is a general agreement that the fumarole gas composition results from the mixing of a deeper magmatic source and a shallow boiling hydrothermal system.

La Fossa crater is characterized by the occurrence of periodical anomalous degassing episodes with increasing output of the fumarole and chemical changes caused by new magmatic fluid inputs (*e.g.* Granieri *et al.*, 2006; Paonita *et al.*, 2002; Chiodini *et al.*, 1995) from a deep pressurized stationary magma body (Granieri *et al.*, 2006; Gambino *et al.*, 2007).

Earthquakes occurring in the area of Vulcano are associated with both fracturing (sporadic swarms of low magnitude shocks) (Aubert and Alparone, 2000) and degassing processes of the geothermal system (Montalto, 1994). La Fossa shallow (<1-1.5 km) microseismicity is linked to hydrothermal activities at Vulcano Island and an increase in its occurrence accompanies periods of anomalous degassing (Chiodini *et al.*, 1992). Microseismic background activity comprises two main groups of events: M-type and N-type, as extensively discussed by Montalto (1994). Long-pe-

Table I. Hypoellipse location parameters of the analyzed earthquakes.

n	Date	Origin time	Latitude	Long.	Depth km b.s.l.	GAP	Nº	RMS	ERZ km	ERH km
1	060809	10:23:44.66	38.4042	14.9702	0.52	174	7	0.07	0.2	0.7
2	060821	01:56:39.88	38.4078	14.9652	0.56	190	6	0.04	0.2	0.5
3	060823	06:12:29.89	38.4028	14.9713	0.49	167	7	0.14	0.2	0.8
4	060827	02:54:44.49	38.4023	14.9695	0.72	156	7	0.12	0.2	0.8
5	060828	03:04:10.34	38.4023	14.9643	0.84	123	7	0.06	0.3	0.6
6	060901	01:23:54.54	38.4030	14.9663	0.78	144	6	0.03	0.3	0.8
7	060901	21:22:11.80	38.4030	14.9653	0.75	138	7	0.14	0.3	0.6
8	060903	00:11:57.58	38.4005	14.9672	0.77	132	7	0.14	0.3	0.6
9	060905	05:57:41.62	38.4043	14.9677	0.93	163	6	0.03	0.3	0.8
10	060905	17:40:14.68	38.4008	14.9683	0.76	139	7	0.03	0.3	0.6
11	060906	23:07:43.17	38.4023	14.9685	0.66	151	7	0.04	0.2	0.7
12	060907	05:53:49.72	38.4030	14.9643	0.76	129	7	0.08	0.3	0.6
13	060909	15:56:09.24	38.4043	14.9628	0.78	118	7	0.06	0.2	0.5
14	060910	23:51:42.95	38.4065	14.9627	0.74	133	6	0.02	0.1	0.6
15	060919	20:02:26.14	38.4018	14.9682	0.83	146	6	0.01	0.4	0.9
16	060921	03:29:21.70	38.4077	14.9655	0.60	189	7	0.22	0.1	0.5
17	060921	05:32:08.16	38.4028	14.9713	0.54	167	7	0.11	0.2	0.8
18	060929	20:56:29.57	38.4052	14.9647	0.70	150	7	0.08	0.2	0.5
19	061006	00:37:20.09	38.4038	14.9673	0.70	201	6	0.02	0.5	0.8
20	061011	02:09:47.41	38.4020	14.9647	0.91	124	7	0.06	0.3	0.6
21	061013	04:17:08.26	38.4060	14.9612	0.73	112	6	0.07	0.2	0.6

GAP = azimuthal gap (degrees); RMS = travel-time residual root mean square (s);
No = number of P arrivals; ERZ, ERH = vertical and horizontal location error.

riod (LP) events at Vulcano have been reported by Godano and Vilardo (1991) who using 1987-1988 data recorded by a temporary network located this seismicity on the SE part of the cone.

LPs are generally related to vibrations and/or volumetric changes of a fluid-filled resonator, in which the fluid has a hydrothermal or magmatic origin (Chouet, 1996). The shape of a resonant structure may vary in relation to the feeding/hydrothermal system features; precise hypocentre locations may help to image this shape.

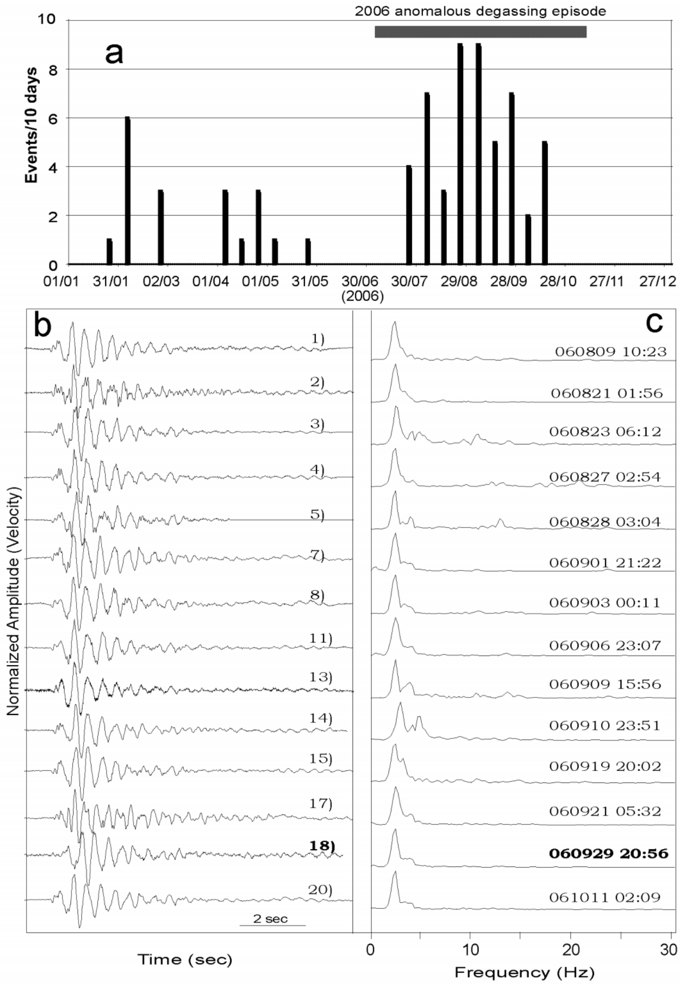

Fig. 2 a-c. Occurrence of LP during 2006 (a), waveforms (b) and spectra (c) of the events analyzed (and relocated). Each event number is referred to tab. I.

Vulcano long periods events are characterized by nearly identical waveforms (multiplets); the application of cross-spectral/cross-correlation techniques on multiplets enables obtaining precise relative locations with accuracy within 5-20 m (*e.g.* Poupinet *et al.*, 1984; Haase *et al.*, 1995).

Concerning tectonic events, these techniques help in reconstructing the seismogenic fault plane (*e.g.* Alparone and Gambino, 2003) while relocation of LPs does not define fault planes but rather volumes (Battaglia *et al.*, 2003). LP precise relocations have been performed on Kilauea Volcano (*e.g.* Battaglia *et al.*, 2003; Wolfe *et. al.*, 2003), Soufrière Hills Volcano Montserrat (Rowe *et al.*, 2004; Green and Neuberg, 2006) and Mt. Etna (Gambino, 2006).

This paper considers 21 LP multiplets by integrating permanent and temporary seismic station data recorded during the anomalous degassing period August-October 2006. We applied a cross-spectrum technique derived from

Frèmont and Malone (1987) to a subset of 14 long-period events, located on SE part of La Fossa crater at Vulcano. The aim of this paper is to obtain a picture of the source volume shape for these earthquakes.

2. Data

Since the late 70's, continuous seismic monitoring activity on Vulcano has been performed by a permanent seismic network composed of four analogical 3C (three components) stations (fig. 1). Recently, new digital 24-bit seismic stations equipped with broad-band (0.2-40 sec) Nanometrics Trillium instruments have been installed at 3 of the 4 stations of the permanent network. In addition, at the end of 2005, three temporary broadband stations were installed on the northern rim of the volcano crater (La Fossa).

During 2006, we recorded about 65 LP events with similar waveforms, 44 of which occurred during August-October (fig. 2a). We focus our analyses on this period in which an increasing release of CO_2-He rich magmatic fluids was recorded at the rim fumaroles (A. Paonita pers. comm.) and no recording problems affected permanent and temporary stations. Vulcano LPs show an emergent onset, short duration and spectra ranging about 1-6 Hz with a single dominant peak at about 2.5 Hz (figs. 2b, 2c).

We recognized a P wave on LP first arrival by high values of the «rectilinearity» (fig. 3) lasting about 0.7 seconds obtained by a three component polarization analysis (Jurkevics, 1988).

3. Location and Q estimation

We obtained suitable locations for 21 microearthquakes (table I, fig. 4) using the HYPOELLIPSE program (Lahr, 1989) which accommodates the difference in altitude of the seismic stations with a local one-dimensional velocity crustal model derived by Falsaperla *et al.* (1985) and previously used by Montalto (1994) and Aubert and Alparone (2000). Hypocenters are located on the eastern and south-eastern sector of La Fossa 0.5-0.9 km depth. Mean epicentre error (ERH) is about 0.7 km and 0.3 km for the focal depth errors (ERZ); RMS values are lower than 0.2 s.

We further analyzed LP waveforms (event n. 18 in table I) using the Sompi method (Kumazawa *et al.*, 1990) that performs a spectral analysis based on an autoregressive (AR) model and determines the complex frequencies (frequency and quality factor Q) of decaying oscillations. Figure 5 reports the diagram frequency (f), *versus* growth rate (g), (g= -2Q/f,) where the complex frequencies for different trial AR orders between 20-60 are plotted (Kumagai and Chouet, 2000). Areas of the diagram that are densely populated represent stably determined complex frequencies and indicate Q-values near 20, while scattered points indicate incoherent noise.

4. Re-location method

The presence of multiplets suggests spatially close sources whose geometry may be inferred using cross-spectral/cross-correlation relocation techniques. The application of these techniques on the P-wave furnish, for tectonic events, the positions above the fault radiating most of the energy, thereby allowing the fault plane reconstruction; indeed their application on LP events provides the relative event starting points allowing to define volumes (Battaglia *et al.*, 2003; Wolfe *et al.*, 2003).

If we assume that at La Fossa LPs correspond to the resonance of a fluid filled volume, then their precise relocation may furnish an image of the container geometry.

We used a cross-spectrum method based on that discussed by Frèmont and Malone (1987). This method permits very accurate relative timing (*dt*) for pairs of earthquakes with very similar waveforms (doublets) and subsequently to perform precise relative relocations. Each doublet comprises a reference event (master event) and one of the other events belonging to the same multiplet.

The differences *dt* in first arrival time between seismograms from the same station of a doublet have been computed in the frequency domain using the phase of the cross spectrum obtained on a short window containing the whole P phase. In particular, *dt* is proportional

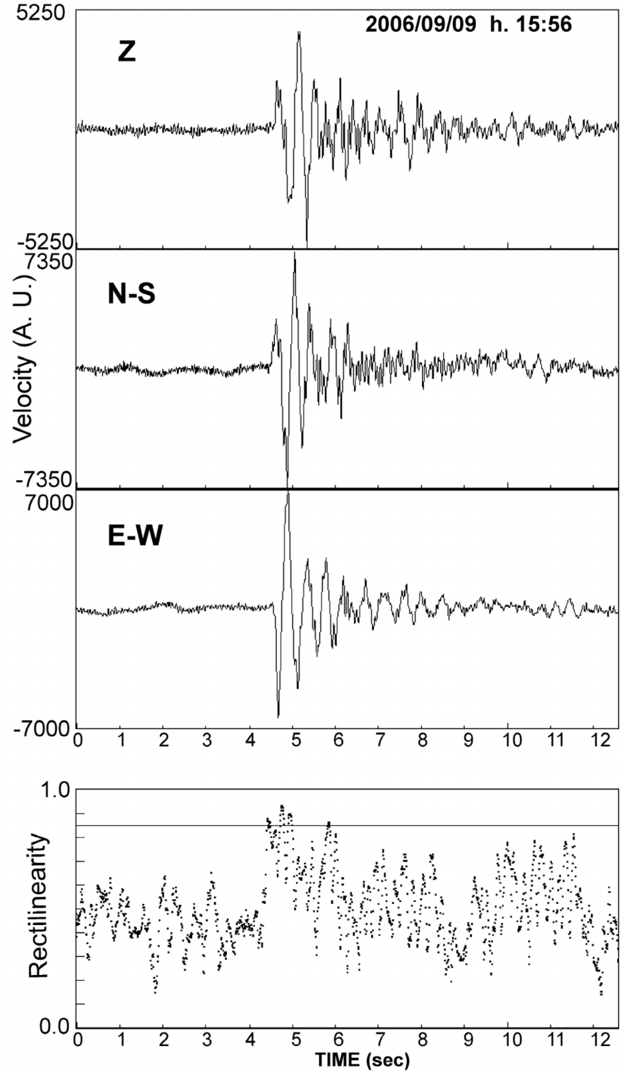

Fig. 3. Example of three component waveforms recorded at STZ2 (Event n. 13 in tab. I) and calculated temporal trend of the rectilinearity.

to the slope of the phase of the cross spectrum which can be written as $\Phi(f) = 2\pi dtf$, plotted *versus* the frequency (f). The degree of success of this procedure depends on the similarity of the waveforms and the signal to noise ratio on all traces.

A parameter measuring the similarity degree between two waveforms is the coherency $C(f)$, defined as the ratio of cross-spectrum modulus over the product of the spectra of the two signals (Frèmont and Malone 1987):

$$C(f) = |\gamma_{s1s2}(f)| \,/\, [(\gamma_{s1})^{1/2}(f)(\gamma_{s2})^{1/2}(f)] \qquad (4.1)$$

where $\gamma_{s1}(f) = S_1(f)S_1{}^*(f)$ and $\gamma_{s2}(f) = S_2(f)S_2{}^*(f)$ are the spectra of the first and second signals, respectively, and $\gamma_{s1s2}(f) = S_1(f)S_2^*(f)$ is the cross-spectrum (* denoting complex conjugate).

Mean coherency calculated above the P-wave frequency interval defines the quality (*Qw*) of comparison between two waveforms. Two very similar signals have a *Qw*>90. A decreasing value of *Qw* indicates a poorer similarity and generally 80 is the threshold below which it is difficult to obtain *dt* with acceptable errors (Frèmont and Malone 1987).

Pairs of events that do not correlate highly may be caused by a low signal to noise ratio; generally smaller magnitude events recorded at distant stations are more difficult to match.

The position and difference in origin time of the second with respect to the master event have been determined using a decomposition in singular values technique discussed by Aki and Richards (1980) (volume II, chapter n. 12) and realized by Frèchet (1985). The parameters needed to obtain a suitable relocation of an event are: the P-wave velocity in the source volume, the take-off angles and azimuths of stations from the reference event. The method requires a minimum number of 5 time differences to obtain the four unknowns (relative position and difference in origin times) with an associated error.

5. Results

The application of the cross-spectrum method (Frèmont and Malone, 1987) on LP Vulcano events limited the definitive set to 14 events; this factor was mainly caused by low signal to noise ratios at IVLP, IVLT and IVUG stations. For each event, we considered the waveforms of the 7 stations of permanent and temporary networks.

Event n. 18 (table I) characterized by the larger peak to peak amplitude was chosen as the master event; the relative timing (dt) for pairs of

Table II. Results of the event relocation.

n master	n event	An. St.	Mean Qw	T. err. (ms)	Dx (m)	Dy (m)	Dz (m)	Ril. err. (m)
18	01	6	96.6	2.5	40.40	23.81	-9.57	16.25
18	02	6	96.0	1.6	52.10	67.53	1.56	6.1
18	03	7	91.4	2.7	86.01	152.02	2.36	9.33
18	04	6	95.0	1.5	80.29	147.11	-8.58	6.79
18	05	7	94.4	2.7	53.75	69.73	5.55	9.56
18	07	6	94.3	1.9	52.15	79.54	-1.03	8.19
18	08	6	97.3	0.7	-4.45	-10.95	-17.20	2.95
18	11	6	96.5	3.0	26.02	37.15	-0.85	11.57
18	13	6	97.2	1.6	24.13	34.48	2.01	3.12
18	14	6	95.6	0.9	24.88	12.34	0.96	4.71
18	15	6	97.6	1.7	11.47	-3.56	1.70	4.83
18	17	6	97.2	0.8	32.57	36.70	-15.01	8.36
18	20	6	94.7	2.6	16.22	12.19	3.72	3.98

An. St. = number of stations used in recolation; Mean Qw = mean of the quality factor at different stations; T. err. = mean relative time error; Dx, Dy, Dz. location differences with associated error (Ril. err.) respect to the master event.

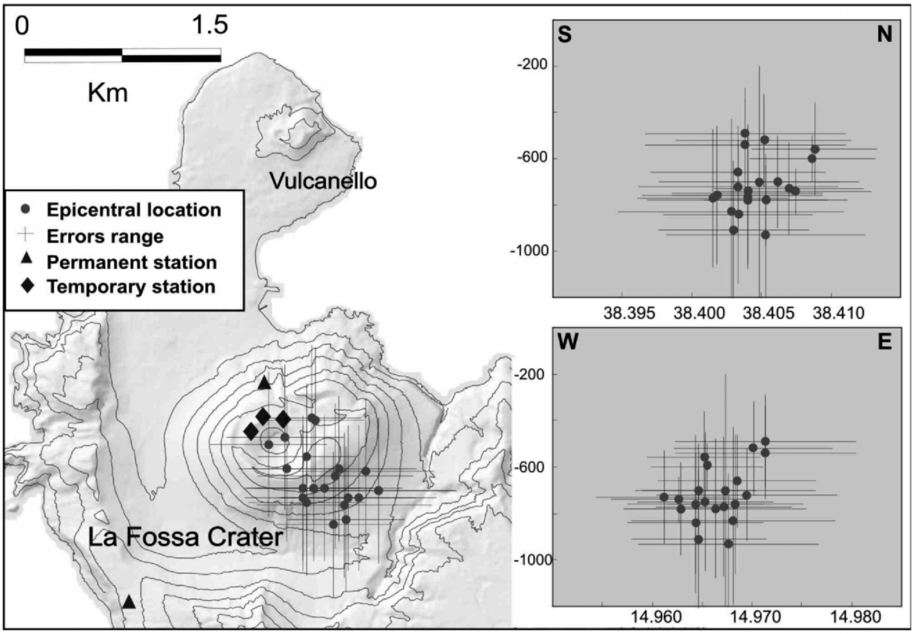

Fig. 4. Epicentral map, NS and EW cross-sections of the located events.

earthquakes was obtained on a 1.28 s window of signal (128 points) starting about 0.24 s before the first arrival, thereby allowing the complete sampling of the P wave train as also performed by Wolfe *et al.*, (2003).

The quality of comparisons (Qw) between the events at different stations always exceeded Qw = 90 somewhat being Qw = 95 between most events (table II); the relative timing between the dt shows errors less than ± 0.003 s. We performed the relative locations using the parameters (take-off angles and azimuths) obtained by analytical location of the master event and a velocity of 1.5 km/s in the source region Falsaperla *et al.* (1985).

Location differences between events range between several meters to several tens of meters with associated errors smaller than 10-15 meters.

LPs relocation (fig. 6) shows the relative positions of the events starting point inside the resonator and clearly describes an elongated shape located 700 m b.s.l. (depth of master event) in a N30-40E direction, 200 m long 40 m wide, only roughly 25 m deep.

We also notice that LPs occurring in the period September 3-October are located in the SW part of the fluid-filled volume with respect to August-September 1 events (fig. 6). However, locations do not show a progressive migration of the source and it is not easy to recognize a possible mechanism.

6. Discussion and conclusions

The magmatic system at La Fossa volcano has been studied through petrologic and geochemical investigations. Analyses on CO_2 fluid inclusions in quartz xenoliths (Clocchiatti *et al.*, 1994; Zanon *et al.*, 2003) suggest that the plumbing system beneath La Fossa consists of small dykes and magma pockets cutting through intrusive rocks at 1.6-2.0 km depth; Nuccio and Paonita (2001) inferred a magma body at depth of 2.5 km by means of geochemical analyses.

We analyzed 21 LPs recorded during an anomalous degassing period (August-October

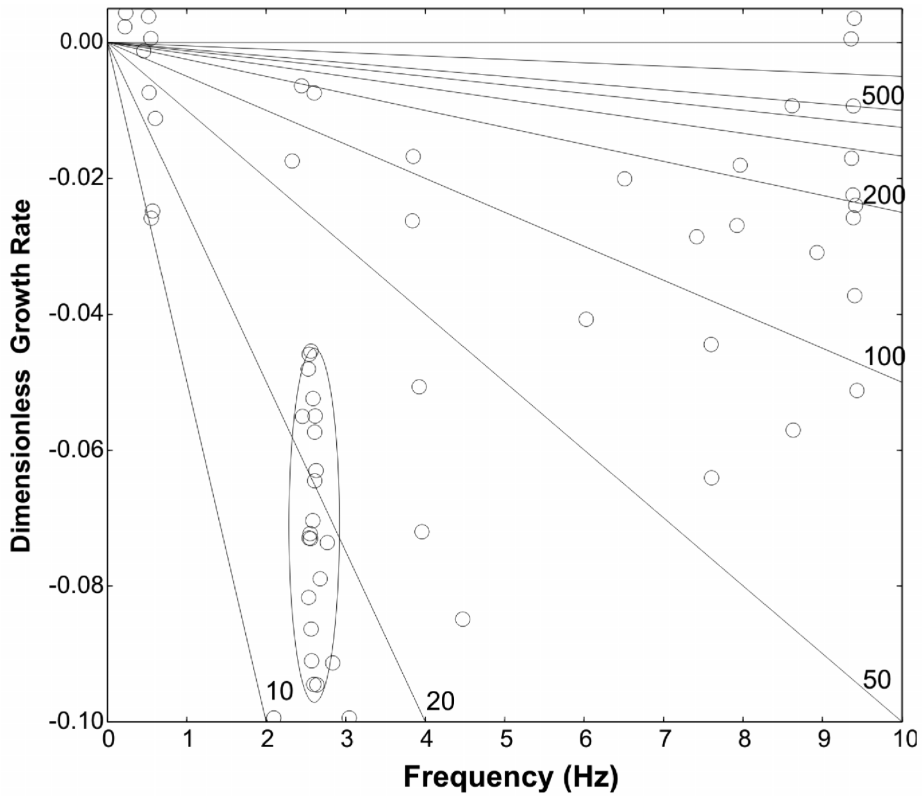

Fig. 5. Frequency, versus growth rate diagram where the complex frequencies for different trial AR orders between 20-60 are plotted. Areas of the diagram that are densely populated represent stably determined complex frequencies and indicate Q-values near 20, while scattered points indicate incoherent noise.

2006) in which an increasing release of CO_2-He rich magmatic fluids was recorded at the rim fumaroles. These events appear to have highly similar waveforms, indicating repetitive and non-destructive source mechanisms occurring within a very limited source volume. We obtained reliable absolute locations of a source positioned under the crater/the SE part of the cone at depth of 0.6-0.9 km (± 0.3 km) b.s.l. (fig. 4).

LPs are shallow and this factor leaves little doubt on the hydrothermal origin of a possible fluid involved in LP occurrence.

Moreover, if we consider a fluid-filled crack model, observed frequencies and low Q-values obtained by Sompi analysis (Q=ca. 20) are explainable by fluids in the form of bubbly water (Kumagai and Chouet, 2000) or alternatively as steam (Kumagai *et al.*, 2005).

It is reasonable that at La Fossa, magmatic fluid inputs modify the hydrothermal system, causing a gradual build-up of steam pressure at depth that may excite hydrothermal fluid-filled containers (LP) and on the surface, geochemical variations.

Results of high precise relocations suggest a trigger region of about 200 m (long) x 40 m (wide) oriented along the NE-SW structural system (fig. 6).

The limited variations in depth (all events are confined within 25 m) may indicate a horizontal source. These kinds of sources are not unusual at other volcanoes such as Kusatsu-Shirane in Japan (Nakano *et al.*, 2003) or Ki-

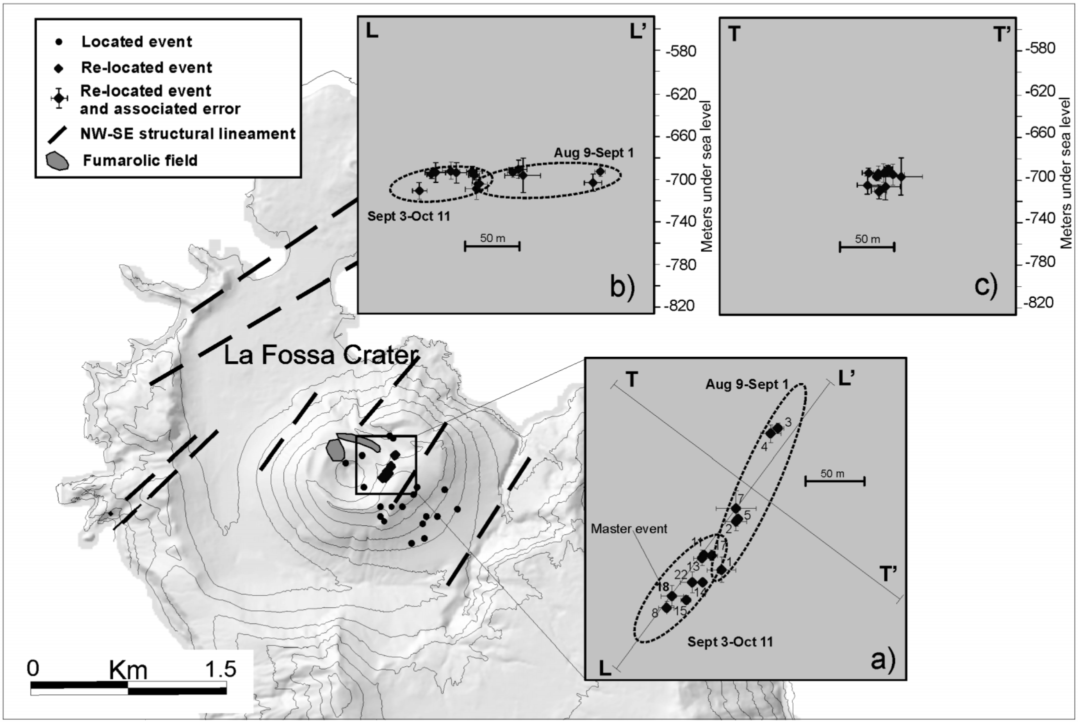

Fig. 6 a-c. Epicentral map of located and relocated events. The insets represent the enlarged map (a), L-L' (b) and T-T' (c) cross-sections of relocated events. Origin coordinates and depth refer to n. 18 event.

lauea volcano (Kumagai *et al.*, 2005).

The presence of a hundred-meter long horizontal source suggests some complexity of La Fossa fluid circulation system, generally thought to comprise only vertical ducts; moreover NE-SW structural trend seems to play a role in the fluid circulation system controlling the fluid-filled cavity trend. This fact seems to be also confirmed by the presence of surface structural NE-SW lineaments (fig. 6), consisting in faults and fracture (Gabbianelli *et al.*, 1991), close to the LP epicentral area.

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